DETECTION AND QUANTIFICATION OF INTERGRANULAR CORROSION AROUND WING SKIN FASTENERS USING THE DRIPLESS BUBBLER ULTRASONIC SCANNER

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INTRODUCTION

Corrosion in all its forms is detrimental to the structural integrity of an aircraft and the ability to detect and evaluate the extent of corrosion is of great importance to the airline maintenance community. The U.S. Air Force intends to extend the use of its transport aircraft well beyond their initial design lifetime and therefore has a need for nondestructive inspection (NDI) methods capable of corrosion detection and quantification. One area of concern in these aging aircraft is the corrosion originating from ferrous wing skin fasteners, particularly that which has progressed just beyond the perimeter of the fastener head but not yet visible as exfoliated material. In 1997, ARINC, Inc.[1] examined several NDI techniques for the Air Force Air Logistics Center in Oklahoma City, OK (OC-ALC) in an effort to identify those methods that demonstrate a high probability of detection (POD) and low probability of false alarms (POFA). Electromagnetic, ultrasonic and thermal techniques were applied to wing skin material samples containing corrosion around the fastener countersink [2].

This paper describes the results from scanning electron microscopy examinations of the materials and corrosion product, the results of the ARINC trials and additional tests for ARINC using the Dripless Bubbler [3,4] ultrasonic scanner. We also describe the rationale behind the setup and data processing scheme used so successfully with the Dripless Bubbler ultrasonic scanner in the ARINC trials. The Dripless Bubbler has since been selected as the primary candidate for wing skin fastener corrosion inspection at the OC-ALC.

ALUMINUM WING SKINS AND CORROSION

The corrosion found in and around wing skin fasteners is a result of the galvanic action between the ferrous fastener and the aluminum wing skin material. Plating of the fasteners and wet sealants applied to the countersink provide some initial measure of protection but corrosion eventually initiates. It starts as pits in the countersink surface and then progresses into the plane of the wing skin sheet. The morphology and orientation of the corrosion are directly related to the microstructure of the aluminum wing skin. Because the wing skin material is a rolled product, the microstructure resembles stacked sheets of grains. Scanning electron microscopy revealed that the corrosion extends out into the plane of the wing skin along grain boundaries. Figure 1a and 1b show the difference between chemically induced corrosion produced by ARINC for this study and naturally occurring corrosion. Diffusion along grain boundaries is much faster than diffusion in the bulk of the grains, so it is not surprising to see needle-like extensions of corrosion product hundreds of microns out into the plane of the wing skin, as in Fig. 1a.. Grains eventually become encircled and then slowly converted to corrosion product, as shown in Fig. 2a and 2b.

The microscopy work also revealed cracks in the corrosion product, which was very easy to locate by increasing the accelerating voltage of the SEM. The corrosion product (an insulator) could not dissipate the charge, which would tend to build up on the edges of the cracks, as shown in Fig. 3. When considering the interaction of ultrasound in the wing skin, it was thought that the impedance mismatch between the aluminum base material and the corrosion product would be the source of reflected sound energy. However, it is believed that the interaction of sound energy with the near-perfect reflector (the crack) is the primary source of reflected energy. This would explain the strong reflections noted from these thin (1-5 mm or ~ 1/100 of a wavelength thick) sheets of corrosion.

Early on it was noted that this type of corrosion was referred to as exfoliation corrosion. The microscopy results clearly indicate that extension occurs along grain boundaries and would therefore be correctly referred to as intergranular corrosion. Only at the later stages, where the extension of the corrosion has migrated and become surface breaking, would the term exfoliation apply.

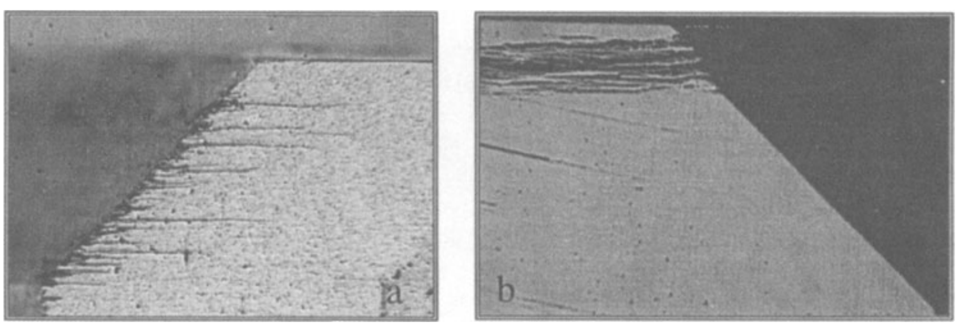

Fig. 1 a) Chemically induced corrosion in KC/C-135 wing skin material and b) naturally occurring corrosion.

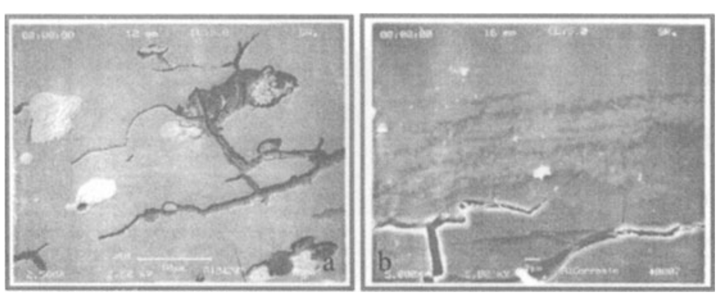

Fig. 2 a) Intergranular corrosion advancing along grain boundaries and encircling individual grains and second phase particles (bar represents 10μm) and b) diffuse growth of corrosion into the bulk of a grain (bar represents 3μm).

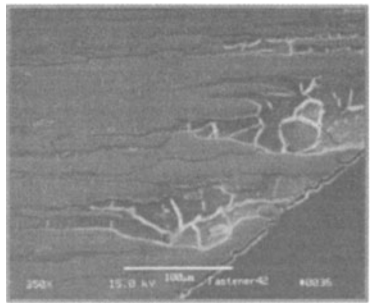

Fig. 3 SEM micrograph showing charge buildup on crack edges in corrosion product (bar represents 100μm).

SCANNING SYSTEM REQUIREMENTS AND SETUP

Prior to the trials, some thought was given to the proper setup of the scanning equipment that would maximize the ability to detect corrosion around the wing skin fasteners. Since the intergranular corrosion occurs in relatively flat planes parallel to the wing skin surface, a normal incidence ultrasonic technique would be a reasonable method for detecting the corrosion extending beyond the fastener but would not be expected to perform well for corrosion under the fastener head. Angled beam techniques would allow inspections under the fastener; work is under way for applying these techniques and will be described in the Discussion and Conclusions section. For normal incidence ultrasonics modes, the Dripless Bubbler has proved very useful for the detection of corrosion in aircraft fuselage skins, laps splices and bonded tear straps as well as disbonds, delaminations, and ply drop-offs in aircraft polymer composite structures and is has been described in [5,6]. The principle advantages of using the Dripless Bubbler are:

- Use of commercial focused ultrasonic immersion probes
- Provides higher spatial resolution, gain and SNR due to use of focused probes
- Provides a stable and consistent coupling and a delay line
- Eliminates the dangers uncontained couplant.

The Dripless Bubbler has demonstrated the ability to provide immersion quality images while operating at any orientation on a aircraft with no loss of couplant (water). The Dripless Bubbler is a scanner independent device that is easily attached to commercially available scanners and requires no adjustments in the equipment's scan control or data acquisition software other than the provision for the delay of the water path. In order to maximize the resolving of corrosion just beyond the fastener and to provide adequate flaw depth information, the following scanning system requirements were adopted:

- Minimum scan step resolution of 0.5 mm
- Minimum sampling rate of 100 Mega-samples per second
- Full waveform capture and post processing capability or a minimum of two (2) simultaneous flaw gates
- Rigid mount of probes to scanners

The minimum step size criteria is based on the minimum diameter of the focused beam used. In the field trials of the Dripless Bubbler, a 15 MHz, 0.5 in. nominal diameter, 2 in. focal length transducer has been used exclusively on aluminum structures because of the relatively low attenuation of the material. The focal spot size of this transducer is approximately 0.75 mm, so a step size of 0.5 mm provides a small amount of overlap with no missed regions. The sampling rate noted provides depth resolution to approximately 0.001 inches (25 microns), which is nominally 2.5-3.75% of the skin thickness is fuselage applications and is easily achieved with modern 8-bit A/D cards. Full waveform capture capability allows the operator to acquire complete data and perform post processing for feature identification off-line and/or away from the maintenance environment. In data acquisition packages that do not have this capability, it is imperative that all the gating conditions be know prior to scanning, and any deviation from the required conditions require adjustments to be made and a re-scanning of the area.

Previous experience with the Dripless Bubbler has shown that a very rigid mount is necessary between the Dripless Bubbler head and the scanner. With even a small amount of backlash, striping is seen in any images produced, a result of the uneven tilting of the unit while scanning back and forth. Unidirectional scanning alleviates this problem but scan time is essentially doubled. The requirement of two flaw gates will be described later.

The focusing conditions for this work are set to locate the focal point at the center of the countersink depth. Exfoliation corrosion is found only in the countersink, so a focal point located at the midpoint of the countersink is the best over-all compromise. For the KC/C-135 wing skins examined in this work, nominal skin thickness is 0.190 in. and fasteners have a nominal 1/8" depth, requiring the focal point of the beam to be located 1/16" below the skin surface.

ARINC TRIAL RESULTS

The ARINC trials consisted of examining samples of KC/C-135 and B-52 wing skin material that was drilled and countersunk for new fasteners. Prior to installing the new fasteners, the sample skins were treated to a proprietary solution that induces intergranular corrosion at an accelerated rate. After exposure, new fasteners were installed and the panels made available to the trial participants. The results from seven participants is shown in Fig. 4. Altogether, three KC/C-135 sample panels contained 60 fastener countersinks, 40 of which were treated, and 15 treated out of 20 fasteners countersinks in the B-52 sample panel. Note from Fig. 6 that the Dripless Bubbler from Iowa State detected all 40 corroded fasteners in the KC/C-135 panels with a single false call, and the Dripless Bubbler from Sierra Matrix, Inc., [7] detected 37 of 40 with no false calls. Figures. 5 and 6, examples of amplitude and time-of-flight C-scans produced from the full waveform data collected, demonstrates why the identification of corroded fasteners was not difficult. With corrosion extending out past the edge of the countersink, a wide "halo" was visible and quite unmistakable when compared to the uncorroded fasteners. Figure 6 also shows the excellent depth resolution demonstrated by this technique.

It should be noted that the Dripless Bubbler did not perform well in the tests on the B-52 panels. Sectioning and metallographic examination showed these panels to contained predominantly pitting corrosion on the countersink, so it would be expected that a normal incidence technique would not do well. The B-52 skin material is a different alloy from the KC/C-135 wing skins and obviously did not react as well with the corrosion accelerator. Out of the 15 treated fastener holes, the Iowa State Dripless Bubbler was able to identify three with one false call.

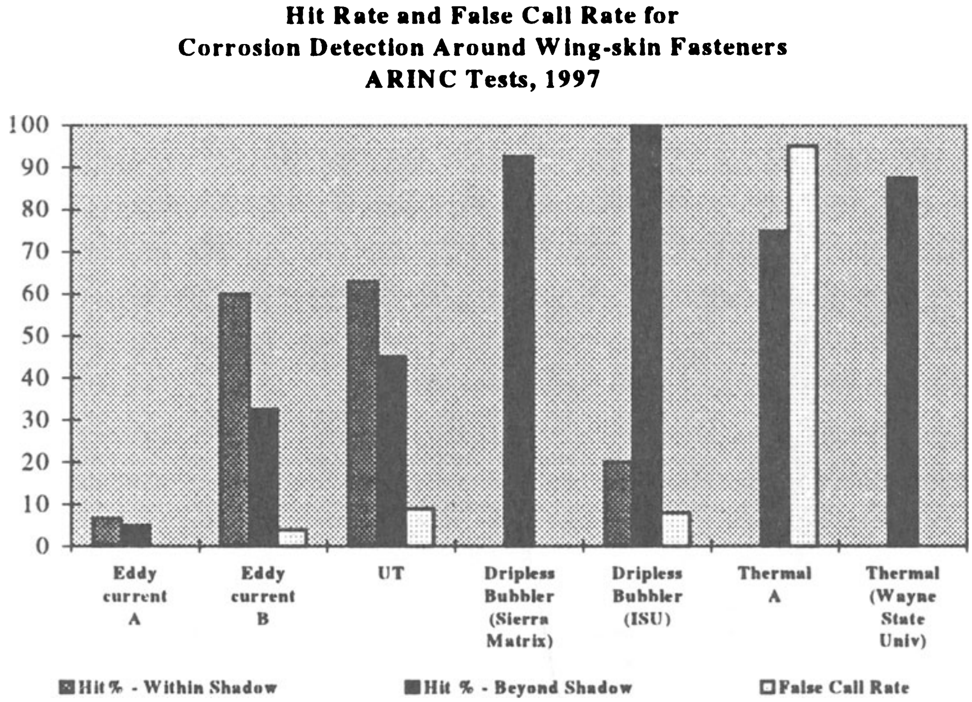

Fig. 4 ARINC chemically induced intergranular corrosion trial results.

After the Dripless Bubblers success in the first trial, ARINC requested that the technique be tested on panels designed to simulate prior repairs. It is not uncommon to find areas that were previously repaired by "blending out" regions visually identified as exfoliation corrosion by grinding off the surface layers to remove the corrosion. After this blending, the fastener holes are re-countersunk to flush the fastener heads when installed.

ARINC fabricated a test panel with varying amounts blending, from slight to severe, out-of-specification blends, with half of the panel painted and half bare. The equipment setup was kept as in the first trial, and as expected, the results were very good. Although the beam was diffracted a small amount do to the curved surface of the blend outs, the corroded fastener countersinks were quite apparent. Figures 7a and 7b show the results from the blended/painted panels, and demonstrate the effect of two different gating

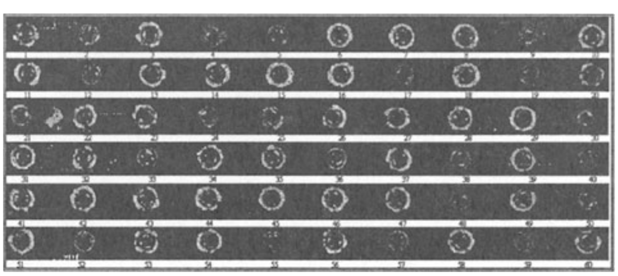

Fig. 5 Amplitude C-scan of KC/C-135 wing skin material with chemically induced corrosion in 40 of 60 fasteners.

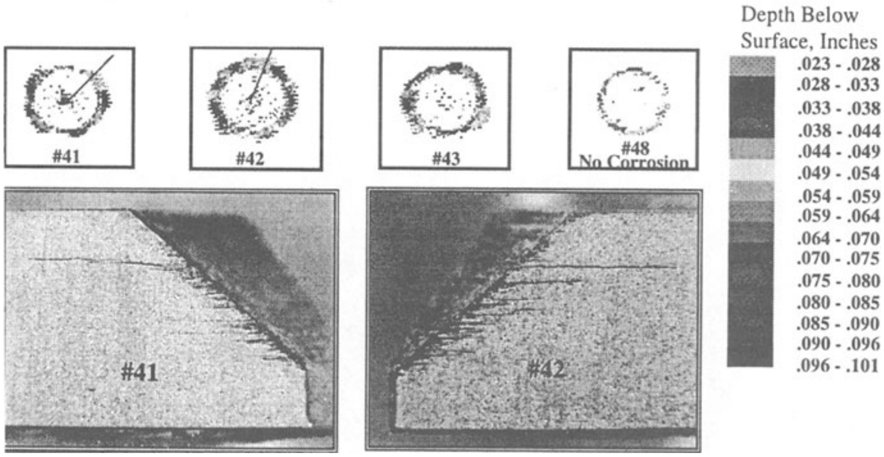

Fig. 6 Time-of-flight C-scans of corroded and uncorroded fasteners and optical micrographs indicating depth of corrosion below skin surface.

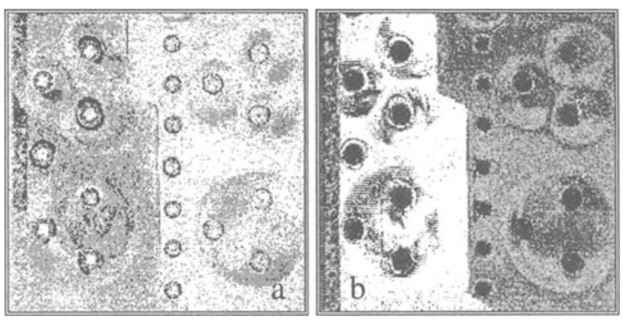

Fig. 7 a) Amplitude C-scan processed from a gate of the countersink region and b) Amplitude C-scan processed from a gate of the back wall amplitude.

schemes. Figure 7a is an amplitude C-scan of the test panel produced by a flaw gate located to detect defects in the countersink region only. Figure 7b is also an amplitude C-scan, but was produced by a flaw gate located to detect only the changes in back wall amplitude reflections. Both gates are capable of identifying intergranular corrosion and have been demonstrated not to be adversely effected by paint or blend outs from prior maintenance. The rationale for using the two gates noted are discussed in the following section.

COUNTERSINK AND BACK WALL GATING

It would not be unreasonable to expect that intergranular corrosion may occur so close to the. The first idea would be to try to move the start of the countersink flaw gate as close to the front wall echo as possible, but flaws very near the surface may not be resolvable from the front wall echo ring-down. If the gate is to close, it may sample the front wall echo and return erroneous indications of corrosion. The proper approach would be to back the start of the countersink region flaw gate off, ensuring that it is far enough away so as not to interact from the front wall echo. This gate will then detect indications in the center and lower part of the countersink. A second gate should then be applied to look only at the back wall signal. If corrosion is present anywhere in the beams path between the front and back walls, it will attenuate the amount of signal reaching and reflecting from the back wall. This gate can give no direct information about the flaws amplitude or time-of-flight, but will act as a indirect indicator of the presence of corrosion.

An alternative "second" gate could be applied to the front wall echo only, but care must be taken to set up the signal gain so as not to have a saturated signal. In this gating scheme, referred to as the "unresolved echo technique", the amplitude of the trailing ring-down is analyzed, since near surface echoes would interact with the front wall ring-down and change its amplitude in small amounts. Image enhancements such as histogram equalization are often required to make visible the small changes seen. This technique also provides no direct information about the near surface flaws, only indications as to their presence.

DISCUSSION AND CONCLUSIONS

The trials on the ARINC test panels have demonstrated that the Dripless Bubbler ultrasonic scanner is capable of detecting hidden intergranular corrosion that has progressed beyond the shadow of the countersink in wing skin materials. This technique has been shown to posses a high probability of detection and low false call rate when used with the equipment specifications and gating schemes mentioned. The gating schemes are key to the success of the technique, particularly with regard to the detection of near surface corrosion.

The Dripless Bubbler has produced immersion quality images in all orientations on an aircraft fuselage with no loss of couplant. The applications to wing skins tested here offered no particular challenges to image quality, and in fact, are quite favorable to scanner operations because the unit does not work against gravity as when scanning lap joints on the side of a fuselage. Performance improvements are needed in detecting early stages of intergranular corrosion, targeting the stage of countersink pitting.

Preliminary work has begun at Iowa State regarding methods of improving the detection early stage corrosion in the countersink. To image the countersink accurately, an angle beam technique making use of a beam bounded off the back wall in a polar scan around the fastener is required. This would require accurate positioning of the scan axis at the center of the fastener. Initial results with a magnetic centering device floating on a cushion of air or water show placement to within 0.25 – 0.5 mm of center consistently. Use of this type of arrangement would naturally lead to a "skip and scan" type of operation, where only that region around the fastener would be scanned, thereby not wasting time scanning the regions between fasteners.

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